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14. ABSTRACT

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During the 1960's, the Captive Trajectory System (CTS) method for store separation wind tunnel testing was developed. The CTS provided a considerable improvement over the hit or miss method, and became widely used in aircraft/store integration programs prior to flight-testing. However, since fairly small-scale models had to be used in the wind tunnel tests, in many cases, the wind tunnel predictions did not match the flight test results. No mechanism was then in place to resolve the wind tunnel/flight test discrepancies.

During this same timeframe, Computational Fluid Dynamics (CFD) had finally matured to the point of providing a trajectory solution for a store in an aircraft flowfield. However, since the computational tools were necessarily (due to computer resource limitations) limited to linear techniques, and since most store separation problems occur at transonic speeds, these tools had limited application.

Recent advances in computer resources have greatly improved the capability of CFD to predict store release characteristics. Instead of using linear or approximate schemes, time dependent Euler and Navier Stokes trajectories could be computed in a reasonable timeframe.

Three international; CFD challenges, held during the last decade of the 20th century, have shown that CFD cannot only match wind tunnel test data, but also predict flight test trajectories for complex stores at transonic speeds. It appears that CFD has matured to the point that it can be usefully integrated into aircraft/sore compatibility programs.

15. SUBJECT TERMS

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Experience in the Use of Computational Aerodynamics to Predict Store Release Characteristics

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"The views expressed are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government."

ABSTRACT

In the early days, store separation tests were conducted in a hit or miss fashion - the stores would be dropped from the aircraft at gradually increasing speeds until the store came close to or sometimes actually hit the aircraft. In some cases, this led to loss of the aircraft, and made some test pilots reluctant to participate in store separation flight test programs.

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Three international CFD challenges, held during the last decade of the 20th century, have shown that CFD can not only match wind tunnel test data, but also predict flight test trajectories for complex stores at

transonic speeds. It appears that CFD has matured to the point that it can be usefully integrated into aircraft/store compatibility programs.

NOMENCLATURE

ACFD	Applied Computational Fluid Dynamics
AEDC	Arnold Engineering Development Center, Wind Tunnel Facility, Tullahoma, Tennessee
AIM	Air Intercept Missile
AIMS	Advanced Imaging Multi-Sensor Systems
AMRAAM	Advanced Medium Range Air-to-Air Missile
ASRAAM	Advanced Short Range Air-to-Air Missile
A_i	Influence Coefficient
B_i	Influence Coefficient
BL	Aircraft Buttline, positive outboard, inches
CFD	Computational Fluid Dynamics
CTS	Captive Trajectory System
C_A	Axial Force Coefficient, positive aft
C_N	Normal Force Coefficient, positive up
C_Y	Side Force Coefficient, positive right wing
C_l	Rolling moment coefficient, positive right wing down
C_m	Pitching moment coefficient, positive nose up
C_n	Yawing moment coefficient, positive nose right
EMD	Engineering and Manufacturing Development Phase
FOT&E	Follow On Testing and Evaluation
FS	Aircraft Fuselage Station, positive aft, inches
GBU	Guided Bomb Unit

H	Altitude, feet
IFM	Influence Function Method
IPT	Integrated Product Team
ITALD	Improved Tactical Air Launched Decoy
JASSM	Joint Air to Surface Standoff Missile
JDAM	Joint Direct Attack Munition
JSOW	Joint Standoff Weapon
M	Mach number
N	Number of Store Segments
NAVAIR	Naval Air Systems Command
NAWC-AD	Naval Air Warfare Center, Aircraft Division
OSD	Office of the Secretary of Defense
P	Store roll rate, positive right wing down, degrees/second
PHI	Store roll angle, positive right wing down, degrees
PSI	Store yaw angle, positive nose right, degrees
Q	Store pitch rate, positive nose up, degrees/second
R	Store yaw rate, positive nose right, degrees/second
SLAM-ER	Standoff Land Attack Missile - Expanded Response
THE	Store pitch angle, positive nose up, degrees
T&E	Test and Evaluation
WL	Aircraft Waterline, positive up, inches
α	Angle of attack, degrees
α_i	Upwash angle of segment i, positive up, degrees
ε	Upwash angle, positive up, degrees
δ_i	Sidewash angle of segment i, positive outboard, degrees

σ	Sidewash angle, positive outboard, degrees
Φ	Velocity Potential
ρ	Density

Subscripts

∞	Freestream
i, j, k	Vector component in the x, y, and z direction
x, y, z	Partial derivative with respect to:
xx, yy, zz	Second partial derivative with respect to:

1.0 BACKGROUND

In the past, store separation testing had to be conducted in a very time consuming, empirical build-up fashion. Stores would be dropped from an aircraft at gradually increasing speeds until the store came too close to the aircraft or occasionally hit the aircraft. In many cases, this led to loss of aircraft; however, there was no other way of determining the safe store release envelope.

During the 1960's, the Captive Trajectory System[1] (CTS) method for store separation wind tunnel testing was developed. The Captive Trajectory System provided a considerable improvement over the "hit or miss" method, and became widely used in aircraft/store integration programs prior to flight-testing. However, the CTS method was not utilized in an integrated approach, since the group conducting the wind tunnel test was generally separated both in organization and location from those responsible for conducting the flight test program and determining the safe separation envelope. Furthermore, since relatively small-scale models had to be used in the wind tunnel tests, the wind tunnel predictions did not always match the flight test results. As a result, resolution of the wind tunnel/flight test discrepancies was often extremely difficult.

By the late 1970's Computational Aerodynamics had finally matured to the point of providing a solution[2,3,4] for a store in an aircraft flow field. Rather than revolutionizing store separation methodology, this new capability inspired an ongoing argument among the Computational Aerodynamicists, Wind Tunnel

Engineers, and Flight Test Engineers. The Computational Fluid Dynamicists claimed that they could finally replace the wind tunnel. The Wind Tunnel Engineers accused the Computational Fluid Dynamicists of being unaware of the complexity of the problem. Finally, the Flight Test Engineers declared that neither group could provide them with the necessary data to conduct a successful flight test program.

During the same time period the Influence Function Method (IFM) was developed[5]. This method allowed for an estimate of store loads based on the aircraft induced flow field impinging on the store. This seemed to offer a bridge to the disagreement between the Computational Fluid Dynamics (CFD) and Wind Tunnel communities, since it could provide store loads in the entire aircraft flow field with just one CFD calculation. However, this method did not readily gain wide spread acceptance in the store separation community. Furthermore, an integrated test and evaluation approach was not truly implemented, since the Flight Test community was still separated both physically and organizationally from the CFD and Wind Tunnel communities.

At that time, the Navy's approach was to use both aircraft and weapon contractors to perform the testing and analysis necessary to clear a new aircraft/weapon configuration. This procedure had several drawbacks, the most serious being that the contractor's involvement usually ended with the start of the flight test program. Therefore the contractor had no means for using the flight test results to improve store separation methodology. Also, no two contractors used the same methodology to predict safe weapon separation prior to flight test.

About ten years ago, the Navy decided to develop a capability/process at the Naval Air Systems Command (NAVAIR) to conduct the analyses necessary for a store separation flight test program. Without any existing capability in this area, the Navy was able to choose among the best attributes of the techniques used by contractors and the Air Force.

NAVAIR realized that the three legs of an integrated approach: analysis, wind tunnel, and flight test are intimately related to each other and provide essential information that can improve the product of each group. Not only does one individual conduct the entire program by the same group, but ideally, the computational

aerodynamics, wind tunnel test planning, trajectory simulation and flight clearance for each point in the flight test program are all managed by the same person or group, that does not have to be an expert in CFD methods or wind tunnel testing, but is competent in their use and, more importantly, knows their limitations. This person or group has the responsibility for ensuring that the flight test program is conducted both safely and cost effectively.

This analysis process has evolved to where the three legs have formed an intrinsic checks and balances system. In order to confirm aircraft/store compatibility, the wind tunnel testing, flight-testing, and computational analyses are dependent upon and essential to one another. The computational analyses determine the critical conditions to be wind tunnel tested, aid in developing the wind tunnel test plan, and verify the wind tunnel test accuracy; while the wind tunnel test confirms the computational model. The wind tunnel test is used to support a flight clearance and plan the flight test matrix, while the flight test corroborates the accuracy of the wind tunnel test data. The flight test also substantiates the computational analyses, while the computational analyses help reduce the flight test matrix.

This approach to store separation has been described previously[5,6,7]. This paper will concentrate on the author's experience in the use of Computational Aerodynamics to predict store trajectories.

1.1 COMPUTATIONAL TECHNIQUES

1.1.1 Navier-Stokes

The Navier-Stokes Equations for a perfect gas are the basic equations that an aerodynamicist would prefer to use when attempting to solve complex fluid dynamic phenomena. In differential form, they are:

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u_j)}{\partial x_j} = 0 \qquad \text{(Mass)}$$

$$\frac{\partial(\rho u_i)}{\partial t} + \frac{\partial(\rho u_i u_j)}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j} \qquad \text{(Momentum)}$$

$$\frac{\partial(\rho h)}{\partial t} + \frac{\partial(\rho h u_j)}{\partial x_j} = \frac{\partial p}{\partial t} + u_j \frac{\partial p}{\partial x_j} + \tau_{ij} \frac{\partial u_i}{\partial x_j} - \frac{\partial q_i}{\partial x_j} \qquad \text{(Energy)}$$

$$p = \rho RT \qquad \text{(equation of state)}$$

$$h = C_P T \qquad \text{(perfect gas)}$$

Where ρ is fluid density, u_i is the velocity vector, p is the pressure, h is the specific enthalpy, τ_{ij} is the stress tensor and q_i is the heat flux vector. The stress tensor and heat flux vector are given by:

$$\tau_{ij} = \lambda \frac{\partial u_k}{\partial x_k} \delta ij + \mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)$$

$$q_i = -k \frac{\partial T}{\partial x_i}$$

Where δij is the Kronecker delta, $\lambda = -{}^2/_3\mu$ is the bulk viscosity, μ is the dynamic viscosity, T is the temperature and k is the thermal conductivity.

Unfortunately, numerical solutions of these equations are available for only simple shapes at small Reynolds numbers. The reason for this is that all the turbulence length scales must be resolved, and computer limitations severely restrict the range of length scales that can be represented. Even for a Reynolds number of 5000 the necessary grid size would be[1] 256 x 256 x 256, while most problems of interest at transonic speeds occur at three or more orders of magnitude higher.

For this reason most numerical solutions of the Navier-Stokes equations use some form of turbulence modeling. The most common of these are the Baldwin-Lomax[2] and the k-ε[3], and have shown reasonable correlation as long as the flow was not highly separated. However, at transonic speeds where boundary layer shock interaction takes place, no turbulence model has demonstrated the capability to accurately represent the interaction in all cases. This unfortunately has led to the specter of turbulence models chasing after the solution.

1.1.2 Euler

The Euler equations, which follow directly from the Navier-Stokes for inviscid flow, are routinely solved for complex aircraft configurations.

$$\frac{\partial \rho}{\partial t} + \frac{\partial (\rho u_j)}{\partial x_j} = 0 \qquad \text{(Mass)}$$

$$\frac{\partial (\rho u_i)}{\partial t} + \frac{\partial (\rho u_i u_j)}{\partial x_j} = -\frac{\partial p}{\partial x_i} \qquad \text{(Momentum)}$$

$$\frac{\partial (\rho h)}{\partial t} + \frac{\partial (\rho h u_j)}{\partial x_j} = \frac{\partial p}{\partial t} + u_j \frac{\partial p}{\partial x_j} \qquad \text{(Energy)}$$

1.1.3 Full Potential

If the flow may be considered irrotational and isentropic, the Euler equations can be reduced to the full potential formulation:

$$(1-\frac{\Phi x^2}{a^2})\Phi xx + (1-\frac{\Phi y^2}{a^2})\Phi yy + (1-\frac{\Phi z^2}{a^2})\Phi zz = -2\,(\frac{\Phi x \Phi y}{a^2})\Phi xy \ -2\,(\frac{\Phi x \Phi z}{a^2})\Phi xz \ -2\,(\frac{\Phi y \Phi z}{a^2})\Phi yz$$

$$\frac{\partial \Phi}{\partial t} = h_0$$

And $\frac{\rho}{\rho_\infty} = \{1 + \frac{(\gamma-1)}{2} M_\infty^2 [1 - \Phi z - \frac{1}{2}\Phi x^2]\}^{\frac{1-\gamma}{\gamma}}$

Where the potential is defined by $u = \Phi x$, $v = \Phi y$, and $w = \Phi z$

1.1.4 Transonic Small Perturbation

If the disturbances can be considered small relative to the free stream velocity, these reduce to the transonic small disturbance equation:

$$(1 - M_\infty^2)\Phi xx + \Phi yy + \Phi zz = M_\infty^2(\gamma+1)\frac{u}{V_\infty}\Phi xx + \frac{2M_\infty^2}{V\infty}\Phi xt + \frac{M_\infty^2}{V_\infty^2}\Phi tt$$

1.1.5 Linear

These further reduce to the Prandtl-Glauert equation:

$$(1 - M_\infty^2)\Phi xx + \Phi yy + \Phi zz = \frac{2M_\infty^2}{V\infty}\Phi xt + \frac{M_\infty^2}{V_\infty^2}\Phi tt$$

For small Mach numbers, the Prandtl-Glauert equation becomes Laplace's equation:

$$\Phi xx + \Phi yy + \Phi zz = \frac{2M_\infty^2}{V\infty}\Phi xt + \frac{M_\infty^2}{V_\infty^2}\Phi tt$$

Although Laplace's equation represents a considerable simplification from the Navier Stokes equations, and cannot be used at transonic speeds, solutions for full aircraft configurations were not available until the early 1960's. The reason for this was that for even simple wing-body configurations, the solution required a matrix inversion on the order of 100 x 100. While this would be a trivial problem these days, at that time this posed a challenge to the latest computers. For this reason, CFD applications to store separation were rare.

1.1.6 Semi-empirical Techniques

The IFM[8] technique assumes that there is a direct relationship between the aircraft flow field along a store and the forces and moments induced by the aircraft flow field on the store. Conceptually, for a store broken into N segments, this is expressed by the relationship:

$C_N = \Sigma A_i^*\alpha_i$, i=1,N

$C_m = \Sigma A_i^*\alpha_i$, i=1,N

$C_Y = \Sigma B_i^*\delta_i$, i=1,N

$C_n = \Sigma B_i^*\delta_i$, i=1,N

The first step in the IFM process is calibration, i.e., determining the store's Influence Coefficients A_i and B_i, which determine its response to the aircraft flow field. It must be emphasized that a store's Influence Coefficients are not an aerodynamic property, but rather a solution to a regression equation relating a series of store aerodynamic loads to a known aircraft flow field. Originally, these influence coefficients were experimentally determined[5]. Subsequently, Keen[7] demonstrated that they could be determined using the IDL code, which was originally developed as a DATCOM type tool to estimate store aerodynamic characteristics. Although the IDL code provides a quick estimate of these coefficients, it cannot be used blindly. The IFM code only allows for an approximate representation of the store's geometry, and wind tunnel or computational tools were used to check the code's predictions.

The second step in the IFM process is the determination of the aircraft flow field. Originally, this was done experimentally; however, with the advent of linear tools[3,6] that could handle arbitrary aircraft/store geometries, aircraft flow fields were determined analytically[8,9].

Using the aircraft flow field and store influence coefficients, an estimate of store aerodynamic coefficients is made everywhere in the flow field, including carriage. Computational methods are used to calculate loads at carriage, which are then used to check the estimated store carriage loads and moments. The store aerodynamic coefficients are then input into a six-degree-of-freedom program to simulate the store's trajectory prior to the wind tunnel test. The simulated trajectories are used to help design the wind tunnel test to ensure that the most critical regions of the store separation envelope are tested.

The IFM technique was improved by Keen, and incorporated into the AEDC Flow-Angle Trajectory Generation Program (Flow TGP) [10]. Interestingly, similar approaches were independently developed in Great Britain (NUFA)[11] and Australia (DSTORES)[12].

2.0 Trajectory Calculations

There are two approaches to calculating a store's trajectory. One would be to perform a time-accurate computation to simulate the trajectory. The process for predicting time-accurate body motion relies on a CFD method to solve the fluid dynamic equations and compute the store loads, and a six-degree-of freedom module to solve the rigid-body equations of motion.

An alternative approach would be to use what is called the grid method in wind tunnel testing. This approach assumes that the free stream aerodynamics are a property of the store alone; while the aircraft induced aerodynamics are mostly determined by the aircraft flow field, with the mutual interference between the aircraft and store playing a secondary role. As may be seen in Figure 1, freestream values for store loads at a specific angle of pitch and yaw would be subtracted from the total loads at those attitudes in a grid under the aircraft to arrive at incremental aerodynamic coefficients. Given the store load at carriage, a six-degree-of freedom program could be used to calculate the store's position and attitude at some small time increment. The incremental grid coefficients could then be added to freestream values at this attitude to arrive at a new set of

total aerodynamic coefficients. These new coefficients would then be used to compute the store's position and attitude at the next time increment.

One advantage of the grid method is that once a set of grid data are available, numerous trajectory simulations can be conducted for that set of data, simulating different inertial and ejector force effects. Numerous comparisons between wind tunnel grid data predictions and flight test trajectory results have demonstrated the validity of this approach.

2.1 Linear Methods

The application of Computational Aerodynamics to the prediction of store trajectories has developed in conjunction with the advance in computer speed and power. The first theoretical store separation code was developed by Nielsen Engineering & Research Inc. (NEAR)[14] in 1971. This code used vortex lattice methods to model the wing, and sources and doublets to model the fuselage. The store was immersed in the flow field, and its loads were obtained by slender body theory. The simplified geometric representation allowed for a trajectory calculation in a reasonable time frame. This code has been extensively improved and modified, and versions are still in use today.

In 1979 the PAN AIR code allowed for a higher order linear calculation of a complex aircraft/store combination. However, since one PAN AIR calculation[3] took more than a day to complete on the super-computer of the time (CDC 6600), using PAN AIR as part of a time dependent store separation code, or using the code to compute a devised grid of aerodynamic coefficients was out of the question. For that reason, hybrid techniques, such as IFM, were developed.

Numerous comparisons[3,8,9,13] with wind tunnel probe data demonstrated that the PAN AIR code could accurately predict aircraft flow fields, even at transonic speeds. PAN AIR was therefore used to compute the store loads at carriage, as well as the flow field underneath the aircraft. IFM was then used to predict the grid store loads underneath the aircraft, which were then input into a six-degree-of freedom program to calculate the trajectory. One example of this approach is described below.

2.1.1 F/A-18E / JSOW

A comparison of the clean (no pylons) F/A-18C and F/A-18E aircraft flow fields was initiated to determine differences which might affect store separation. A PAN AIR model was developed and validated using wind tunnel pressure data measured on the wing.

The preliminary analysis indicated that the F/A-18E increased inlet area, which produced an increased aircraft area ratio, had a significant impact on the aircraft flow field, and might have a detrimental effect on store separation.

Prior to the wind tunnel tests at AEDC, flow field angularity predictions were made utilizing the PAN AIR model previously developed. Comparisons between test data and analytical predictions correlated very well for both the F/A-18C and F/A-18E aircraft, Figures 2 and 3. This confirmed that the PAN AIR model of the F/A-18E aircraft is a good representation and should give good qualitative answers even at low transonic speeds.

Validation of the PAN AIR model of the F/A-18E provided an opportunity to evaluate the effects of the aircraft flow field on the trajectories of stores separating from the aircraft. Since the IFM technique had been used for the F/A-18C/JSOW program, it was used again to predict JSOW trajectories from the F/A-18E aircraft.

Using the JSOW IFM Influence Coefficients, which had been validated for the F/A-18C aircraft, and the F/A-18C and F/A-18E flow fields previously determined, trajectory predictions were made for the JSOW store from the F/A-18E aircraft. These trajectory predictions were compared to the equivalent trajectories from the F/A-18C aircraft. As displayed in Figures 4 and 5, the IFM predictions for the JSOW trajectories from the F/A-18E were in excellent agreement with the CTS test data for the store on the midboard station with a tank inboard, but underpredicted the yawing moment for the store on the inboard pylon. Considering the fact that the predictions were made three years prior to the wind tunnel test, it is clear that the IFM technique can give a good qualitative estimate of aircraft flow field effects.

2.2 CFD Challenges

With continuing advances in computer power and speed, it became possible to solve the Full Potential, Euler and even simplified Navier-Stokes equations. In particular, the development of the CHIMERA[4] approach, which allowed a separate grid around the store and aircraft, and unstructured[15] techniques, true CFD calculations of store trajectories became practical. This has led to several CFD Challenges to determine how close CFD can come to matching wind tunnel or flight test data.

2.2.1 Wing-Pylon-Generic-Store

Over the past several years there have been several organized efforts to validate, demonstrate and accelerate the insertion of CFD methods into the store certification process for external stores carriage and release. Several significant efforts have been documented in AIAA conference proceedings. The first of these was the Wing/Pylon/Finned-Store, which occurred in Hilton Head, SC, in the summer of 1992. An extensive set of wind tunnel store carriage and separation data for CFD code validation were made available for a generic wing and store geometry[16]. Although Euler[17,18] and thin layer Navier-Stokes[19] (TNS) solutions were in good agreement with these test data, solution times on the order of 5 days[20] on the Cray YMP made such tools impractical for everyday use. Madson later demonstrated[21] that the TranAir full-potential code could give results of similar quality in a fraction of the time required for the higher order codes, as may be seen in Figure 6 and Figure 7.

2.2.2 F-16-Generic-Store - ACFD Challenge I

Several years ago the Office of the Secretary of Defense (OSD), under the Central Test and Evaluation Investment Program (CTEIP) funded a tri-service research project termed Applied Computational Fluid Dynamics (ACFD) for store separation. This project is meant to provide analysis tools that effectively use

Computational Fluid Dynamics (CFD) for store certification analysis. ACFD will provide the needed tools that will reduce DOD dependence on wind tunnel and flight-testing.

ACFD is not intended to replace the wind tunnel in the near future; rather it will be used to determine the critical regions of the flight envelope to help structure the wind tunnel test, and to explain any wind tunnel anomalies and help structure the flight test program. The objective of the program is to provide upgraded analysis tools that will support store certification requirements at less cost and in less time.

The first ACFD sponsored conference was concerned with the F-16/Generic Finned Store[21-27] occurred in New Orleans in the summer of 1996 (ACFD Challenge I). At the end of the meeting, the ACFD tri-service technical leads evaluated the CFD tools that were used to predict the F-16 Generic store carriage loads. The evaluation concentrated on the following characteristics:

1. Time required to obtain a solution, which included the time required to convert the geometry into a form compatible with the code's pre-processor, the time required to obtain a surface and volume grid, and the time required to ensure that the solution obtained was properly converged.

2. The accuracy of the solution.

3. Code efficiency or time required to obtain a meaningful minimum number of independent solutions; one solution, at one Mach number and angle of attack is useless for determining a store's trajectory. This time is determined both by the difficulty in generating a new geometry and the running time for each case.

4. Potential for production use: the overall goal of the ACFD project.

The following CFD codes were evaluated for the project:

SPLITFLOW[21] by Lockheed.

TranAir[22] by NAWCAD

USM3D[23] by NAWCAD

OVERFLOW[27] by NASA Johnson

STORESIM[26] by Wright Labs

STORESIM never obtained a valid solution and was dropped from the study.

A summary of the results of the evaluation follows:

1. The time required to obtain a solution, according to the reports submitted at the end of the project, were hard to compare since it could be influenced to a large extent by the past experience of the code's user. The NAWCAD efforts were purposefully conducted by individuals with no prior experience with the particular codes used, while individuals with varying degrees of prior experience with the tools conducted the other efforts. However, based on the information provided by the authors, TranAir took about two weeks to obtain a solution, SPLITFLOW and USM3D took about a month for a solution, while OVERFLOW took about three months for one solution. On that basis the TranAir code was judged the best.

2. The accuracy of the solution was also hard to determine, since SPLITFLOW had 24 independent solutions, some of which were excellent while others were terrible, while OVERFLOW had only one. However, based on the one common solution for the two codes, it appears that the OVERFLOW solution was slightly better in terms of the pressure comparisons. The USM3D and TranAir solutions were comparable to each other, but not as good as the OVERFLOW comparison.

3. Since SPLITFLOW provided 24 solutions in the four months of the project, TranAir and USM3D provided 8 independent solutions, and OVERFLOW had only one solution, the SPLITFLOW code was clearly superior in this respect.

4. For transition potential SPLITFLOW appears to be clearly superior to all the others. TranAir, which gives answers of equivalent accuracy with considerably less set up time seemed slightly better than USM3D. OVERFLOW, as the Navy had previously determined, is too cumbersome to provide meaningful results in the time required for store separation projects.

Many important lessons were learned; however, the experimental test case did not include flight test data ("real" store trajectories). Because of this limitation, store certification engineers continued to express skepticism towards the accuracy of CFD methods. Also, the CFD community raised concerns about the credibility of portions of the wind tunnel test data, criticizing scale, model support interference, and wall effects. Therefore, there was a desire within the ACFD[15] program to reconcile these issues by conducting additional analysis by using a data set that included both wind tunnel and flight test data.

2.2.3 F-18C/JDAM - ACFD Challenge II

Large sets of wind tunnel and flight test data existed for the F/A-18C JDAM configuration, Figure 8. During the flight test phase, both photogrametrics and telemetry were used to track the position of the store during releases. Out of these tests, two release conditions were selected for this CFD Challenge. The basis for these two cases included the following considerations: 1) matching aircraft and store geometry in both wind tunnel and flight tests; 2) correlation between wind tunnel data and flight test data; 3) possession of both high transonic and low supersonic cases with interesting miss distance time histories; 4) ability to publicly release the wind tunnel and flight test data to an international audience.

2.2.3.1 TEST CASE PARAMETERS

The test cases selected were M = 0.962 at 6,382 ft. (flight 13) and M = 1.05 at 10,832 ft. (flight 14). Both cases were for the aircraft in a 45-degree dive.

For these two test cases, the configuration geometry for the wind tunnel and flight test is shown in Figure 8. The JDAM is mounted on the outboard pylon, with the 330-gallon fuel tank on the inboard pylon. The SUU-65 BRU-32A/A ejector rack provided a nominal peak force of 7,000 pounds for both fwd and aft cartridges. As may be seen in Figure 9, an Euler prediction of the Mach number distribution at M =0.962 indicates strong transonic interference effects.

2.2.3.2 FLIGHT TEST RESULTS

Both Captive Trajectory System (CTS) grid data, and store aerodynamic force and moment data measured on the wing pylon were available for this aircraft configuration. These data were input into a six-

degree-of-freedom trajectory code before the flight tests were performed. Parametric variations on flight conditions and store aerodynamic forces were performed to ensure that the flight test could be safely accomplished. After the flight tests were completed, the trajectory simulations were again performed, with the actual flight conditions used to try to match the flight test results These predicted trajectories were used as the metric for the CFD Challenge II, and were not given to the participants until just prior to the meeting

2.2.3.2.1TEST FLIGHT #13

Flight test #13 was conducted on July 10, 1996. The store was released in a 43 degree dive at 6,382 ft. at M = 0.962. The telemetry and photogrametric data were not in good agreement with each other for the vertical displacement. Since inertial effects (store mass and ejector force) largely drive the vertical displacement, the relative Z displacement is usually the easiest to predict. The discrepancy in Z was attributed to the effects of aircraft motion caused by store release.

As may be seen in Figure 10, the predicted pitch and yaw attitudes at M = 0.962 were in excellent agreement with the flight test results. The roll attitude was not well predicted.

However, roll attitude, which is the hardest to predict, fortunately has a minimal impact on the trajectory. The photogrametric results are not shown, since they were considered to be less accurate than the telemetry data.

2.2.3.2.2 TEST FLIGHT #14

Flight test #14 was conducted on August 29, 1996. The store was released in a 44 degree dive at 10,832 ft. at M = 1.055. The telemetry and photogrametric results for the displacement again showed a large discrepancy in Z.

The predictions using the wind tunnel test data were again in excellent agreement with the flight test data, Figure 11.

2.2.3.2.3 MISS DISTANCES

The most important parameter for safe store separation is the ability to accurately predict the store miss distance, which is the smallest distance between any part of the store and aircraft during the early part of the

trajectory. The trajectory simulation used the force measured for ejection from the F-18 centerline to compensate for aircraft motion. As may be seen in Figures 12 and 13, the miss distance predictions were in excellent agreement with the test data. The disagreement between the photogrametric and telemetry predicted miss distance is attributed to the fact that the telemetry could not take aircraft motion into account.

2.2.3.3 ACFD CHALLENGE II PAPERS

2.2.3.3.1 General

Each participant was requested to include in his or her paper:

1. a description of the CFD and trajectory integration methods used to produce the estimates of the trajectory;
2. a description of the methods and resources required to produce the computational grid;
3. estimates of carriage loads, the position and attitude of the store throughout the computed trajectories and an estimate of the miss distance versus time; and
4. metrics of the CFD process used, including convergence rate, man-hours and time required for grid generation, computer resources used and an estimate of the expertise of personnel required to replicate the results.

Eight papers by Cenko[28], Hall[29], Tomaro[30], Woodson[31], Welterlen[32], McGroy[33], Fairlie[34], and Benmeddour[35] were submitted for ACFD Challenge II. The meeting was held at the AIAA Annual meeting in Reno, Nevada, on January 12th, 1999.

The first paper[28] described the wind tunnel and flight test results, while the other seven described the application of seven different CFD codes to the problem. Two other papers[37, 38] were provided at a later date.

2.2.3.3.2 ACFD Challenge II Overview paper

Cenko outlined the background to the Challenge and the sources of the data used. The wind tunnel data consisted of both CTS grid and carriage force and moment data measured on the wing pylon, conducted in the CALSPAN 8-ft. transonic wind tunnel. The grid and carriage data were for a 6% model while the freestream data from both 6% and 22% scale models were available. As was seen in Figures 10-13, the wind tunnel data were in excellent agreement with the flight test results.

2.2.3.3.3 CFD Research Corporation.

L. Hall presented the results of the CFD research code for the F-18/JDAM configuration. These results were significantly different from the other seven codes presented, since the trajectory calculations were run in a time dependent mode. At the time of the meeting, the trajectory had run for only .05 seconds; however, the predictions shown were in good agreement with the test data. One drawback of using time dependent (as opposed to steady state) trajectory calculations is that it takes a very long time to get one solution, and, if any of the parameters change, another solution would take just as long.

2.2.3.3.4 Air Force Wright Research Lab

Tomaro presented the F/A-18C/JDAM carriage loads and trajectory analyses conducted by AFRL/VAAC. The study included the use of computational aerodynamic (CFD) and 6DOF rigid-body, trajectory generation techniques. The two methods were not coupled into a single simulation package: the CFD method simply provided the aerodynamic loads database to the trajectory generator which was run independently in a carriage-loads decay manner. The CFD portion of these analyses used the AFRL/VAAC 'Cobalt' flow solver.

For the F/A-18C/JDAM carriage cases, several tetrahedral grids were produced with the NASA GridTool/VGRIDns unstructured mesh generation system. The primary grid used in subsequent carriage loads analyses consisted of 6.62 million cells (half-model for symmetry) with viscous boundary layers (approx. 4 million cells) about all components of the F/A-18C and JDAM. About one-month of calendar time was required to generate an 'appropriate' mesh, i.e. no negative volumes, crossed faces, etc. Subsequent Cobalt solutions required about 10.1 GBytes of main memory and the following timings:

M = 0.962	M = 1.055
50 nodes (CPU's) IBM SP2	32 nodes IBM SP2
17.69 hours wall-clock	26.87 hours wall-clock
17.22 hours CPU/node	6.27 hours CPU/node
(861 total CPU hours)	(841 total CPU hours)

Isolated freestream JDAM viscous grid generation and flow solutions (alpha and beta sweeps) required less than 3 weeks turnaround for both Mach numbers. Thus, within two months calendar time, the CFD portion of the Challenge was completed.

After the carriage and isolated, freestream JDAM aerodynamics were provided by Cobalt, trajectories were generated using the NAWCAD NAVSEP[2] program. The carriage-loads decay method was used to account for mutual interference effects between the F/A-18C and JDAM. NAVSEP requires, in addition to the aerodynamic forces and moments and the aircraft induced flowfield, the store's inertial properties, damping coefficients, and ejector-model characteristics. It then calculates trajectories in a matter of seconds on any computer platform.

The predictions for the pitch and yaw motion of the store for the M = 0.962 and M = 1.05 were in excellent agreement with the test data, although the pitch attitude was somewhat overpredicted. This implies that the predicted carriage pitching moment was larger than that in flight. The roll motion was not well predicted. However, since rolling motion has traditionally been the hardest part of the trajectory to predict, and generally has little influence on store miss distances, the lack of rolling motion correlation is of small consequence.

2.2.3.3.5 Naval Air Warfare Center.

Woodson[19] presented comparisons for SPLITFLOW, USM3D, and PUMA, an unstructured, viscous code developed at NAWCAD.

Only viscous-store results were computed using the USM3D code. The code for both cases was run for 2000 iterations using a (Courant-Friedrichs and Lewy) CFL of 0.1 initially ramping up to 100 over the first 500 iterations and then continued at 100 for the remaining 1500 iterations. The solutions converged to a steady state value in approximately 500 iterations with the residual reduced about three orders of magnitude. The solutions were run on a Cray C90 and required 315 mega words (MW) of memory and a total of 48.44 hours of CPU time for case 1 and 57.46 hours for case 2. Multitasking was employed using ten processors for a wall clock time of

approximately six hours for case 1 and eight hours for case 2 (average concurrent CPUs = 7.5 and 6.96, respectively).

Two solution approaches using SPLITFLOW were conducted: (1) inviscid, and (2) viscous around the JDAM store. By assigning different material numbers (i.e. wings, pylons, stores, body, inlet, outer boundary, etc.) to the various components of the configuration different boundary conditions may be applied so that the prismatic grids may be generated only on those parts of the geometry where viscous effects are anticipated to be important and neglected elsewhere. Both cases were run for 2000 iterations using a CFL number of 1.0 and a turbulent CFL number of 0.1. The solutions were run on a Cray C90 requiring 256 MW of memory and a total of 58.56 CPU hours for case 1 and 81.29 hours for case 2. Multitasking was employed using four processors for a wall clock time of approximately 34 and 48 hours (average concurrent CPUs = 1.75 and 1.7, respectively). The longer run time for case 2 was caused by sliver cell problems aft of the shock at the pylon trailing edge so a smaller global cell size was employed which resulted in the code reaching its maximum number of cells much sooner than it did for case 1. Both cases achieved about three orders of magnitude reduction of the residuals. The inviscid solutions required about one half the run times of the viscous store results (26.50 and 40.56 CPU hours, respectively).

Both of the PUMA runs were inviscid and were performed using between 32 and 64 nodes of the IBM SP-2. Each run was converged two orders of magnitude using first order spatial accuracy. Then this first order solution was used to initialize the second order runs. Unfortunately, it was possible to converge the second order solution only about 1-2 orders in the residuals.

Although the results presented were impressive and showed good correlation with the test data, the JDAM strakes were not modeled in the analysis. It is not known whether the results obtained were fortuitous, or that the strakes have little impact on the trajectories.

2.2.3.3.6 Lockheed Martin

Welterlen[20] presented both viscous and inviscid SPLITFLOW results. The viscous grid required 800,000 Cartesian Cells, and an additional 1,044,207 prismatic cells on the surface. The inviscid solution

required approximately 120 CPU hours on a HP 9000 using 8 V-2250 processors. The viscous results required about 250 CPU hours on a Cray J-90.

The predicted carriage loads were in close agreement with the test data; however, the inviscid results matched the carriage loads better than did the viscid. Since the SPLITFLOW code was coupled to a six-degree-of-freedom code that was developed for this purpose, it was not possible to determine whether the relatively poor predicted trajectories achieved were due to SPLITFLOW or the trajectory code.

2.2.3.3.7 Aerosoft Inc

The sixth paper from Aerosoft Inc using the GUST solver package was withdrawn. McGroy later presented results that were similar to the others shown in this paper, but these have not been made available at this time.

2.2.3.3.8 DSTO Australia

Fairlie then presented computations[22] using the RAMPANT code supplied by Fluent Inc.

The trajectories were simulated using the Defense Science and Technology Organization Release Evaluation Suite (DSTORES). This approach is similar to that used by Tomaro and Woodson.

The initial grid as input to the RAMPANT Solver consisted of just over 1.05 million tetrahedra. A typical RAMPANT run consisted of about 200 iterations with the value of the CFL number set to 0.5, followed by about 300 iterations with CFL set to 1.0. This was generally sufficient to reduce the normalized residuals of continuity, x-, y- and z-momentum and energy by between two and one half and three orders of magnitude compared with their initial values. At this stage, the grid was adapted in regions in which the static pressure gradient exceeded a particular value (initially set to 10% of its maximum value, but varied depending on the number of tetrahedra generated in the new grid) in an attempt to better define shock waves. After adaptation, the grid generally contained somewhat more than 1.25 million tetrahedra. The solution was then iterated for up to a further 500 iterations. After an initial transient created by the adaptation of the grid, the residuals once again fell to their previous, or even lower values.

All computations were carried out on a Silicon Graphics Origin 2000 server. This machine has sixteen R10000 processors running at 250~MHz and is equipped with 4~GB of memory. Typically, the initial 500 iterations on the un-adapted grid required a little less than 40 hours of CPU time on a single processor, and occupied approximately 460~MB of memory. After adaptation, the additional 500 iterations used somewhat more resources, the exact amount depending on the number of tetrahedra in the adapted grid. While the vast majority of the calculations presented were carried out on a single CPU, the RAMPANT code may be run in parallel. Thus far, no more than four parallel processors have been used, yielding a speed-up of just over 3.8 compared with a single processor.

The RAMPANT predicted carriage loads were input into the Australian six-degree-of-freedom code, in conjunction with the experimental store freestream data, and the trajectories were calculated in a manner similar to those in Reference 17. The Australian code has an unusual feature that allows it to calculate a yaw restraint between the pistons and the store during the ejector stroke, which lasted for approximately 0.07 seconds. The yaw attitude would have been in excellent agreement with the flight test data if the prediction were displaced by 0.07 sec. It appears that for this case, the trajectory code did not properly account for the constraint between the pistons and store. However, there have been numerous flight test cases where the store was clearly constrained in yaw during the ejection stroke. The constraint feature will become more useful once it has been calibrated with flight results.

The pitch attitude prediction was in reasonable agreement with the test data, although it overpredicted the test data by approximately 20% at both Mach numbers. The roll attitude was in excellent agreement with the flight test results; the yaw constraint might have fortuitously helped to constrain the roll.

2.2.3.3.9 NRC IAR Canada

The last paper described[23] the quasi-steady CFD approach developed at the Institute for Aerospace Research (IAR) of the National Research Council of Canada (NRC). It consists of three different modules:

1. A steady-state 3D unstructured inviscid solver, FJ3SOLV;
2. A 6-DOF Store Separation Model (SSM); and

3. A grid motion technique.

Each of these modules could be used separately.

To apply the IAR approach to the F/A-18C JDAM CFD Challenge, the three modules were coupled in a quasi-steady mode using the following methodology:

For a given store position, compute the steady-state aerodynamic loads acting on the store using FJ3SOLV. Feed the CFD predicted aerodynamic loads into the 6-DOF SSM and, for a small time increment compute the new store CG location and angular orientations.

If grid motion is possible, move the store and grid nodes using spring analogy technique to store's new position and go to step 1. If grid motion is not possible or grid cells become inadequate after node movement, move the store to its new position, generate a new grid, interpolate the solution to the new grid from the previous one and go to step 1. Starting from a clean configuration, suitable for griding, and with a time step of 0.02 sec., it took about two weeks to compute the JDAM trajectory for a time period of 0.24 seconds. The Canadian results were very similar to the others shown.

2.2.3.4 OTHER RESULTS

Two other organizations that tried to take part in the Challenge were not able to present their results in Reno. Their approach differed from all the previous papers since they used a structured grid approach based on the Chimera formulation. The results presented are described below.

2.2.3.4.1 AFSEO

The Applied Computation Fluid Dynamics (ACFD) group within the Air Force Seek Eagle Office (AFSEO) also computed the F/A18C/JDAM Challenge cases[24] using a fully time accurate CFD simulation.

The ACFD group utilized the Beggar flow solver originally developed at the Air Force Wright Laboratory at Eglin AFB with development continuing within the AFSEO by the ACFD group.

The separation of the JDAM from the F/A18C at Mach 0.962 was simulated using the Beggar code assuming inviscid flow. The grid system for the F/A18C, the JDAM, and assorted auxiliary grids utilized a

total of 39 single block grids and 12 multi-block grids with a total of 95 grids and 2.8 million grid points. The JDAM grid alone contained 360,000 points. The grid system was generated in approximately one-man month.

The separation simulation was run at a physical time step of one millisecond and was terminated at a solution physical time of 0.42 seconds. The solution was run on 16 processors for the flow field solution with another 2 processors used for the grid assembly process. The execution time varied somewhat with an average wall clock time of 160 seconds per time step on an SGI Origin 2000 with 250MHZ MIPS R10000 processors. Thus, a simulation out to 0.25 second in physical time could be performed in less than 12 hours. Each flow solver process utilized between 75 and 132 Megabytes of memory with the total memory requirements of 1.6GB for the flow solver. Each of the two grid assembly processes utilized another 512MB of memory.

The agreement shown in general was excellent, with the inviscid results slightly over predicting the pitch and yaw angles. The preliminary viscous results showed an improvement in the agreement with the flight test data. The inviscid prediction of the roll angle was generally good and captured the general trends. The viscous agreement degraded at later times when the JDAM was at large yaw and pitch angles.

2.2.3.4.2 AEDC

AEDC performed time-accurate viscous computations to simulate the trajectory simulations for both flight release conditions[25] utilizing the Chimera overset grid approach. The process for predicting time-accurate body motion relies on four codes, NXAIR to solve the fluid dynamic equations, PEGASUS to define the inter-grid communications, FOMOCO to compute the store loads for overlapping surfaces entities, and SIXDOF to solve the rigid-body equations of motion.

The F-18C surface definition was prepared from a CAD definition. A significant portion of the effort involved preparing the aircraft surface from the CAD definition, which was accomplished in approximately one month. Volume grid generation and setting up the PEGASUS inputs required about two to three weeks. To reduce the number of grid points to define the boundary layer, wall functions were utilized. The overall grid system, comprised of 7.0 x 10^6 mesh points, is distributed over 66 individual overset meshes (5.2 x 10^6 points over 47 meshes for the F-18C and 1.8 x 10^6 over 23 meshes for the JDAM). All detail of the JDAM was

modeled including the strakes and fin gaps. The aircraft engine duct was modeled to compute flow through the duct. Lateral symmetry about the aircraft center plane was assumed, and only the port side of the aircraft was modeled.

Given the release conditions and ejector model, the two separation trajectories were simulated by using the aforementioned codes. The turbulent Navier-Stokes equations were solved with the two-equation SST turbulence model. Duct flow was established to a corrected mass flow rate at approximately 145 lbm/sec for both release conditions. The steady-state solutions of the flow field about the carriage configuration were performed until convergence was achieved for the store loads to approximately three decimal places. The steady state and trajectory computations were performed on a SGI Origin 2000 R10000 and level loaded over 16 processors. Computations to determine the steady-state carriage loads required approximately 600 steps for each case. The time-accurate computations took 500 time steps to compute the 0.4-second trajectory. The total CPU time to complete one case (including both the steady state and dynamic portion of the computations) was 2900 CPU hours (1400 for the steady-state solution and 1500 for the dynamic solution). PEGASUS requires approximately 25 percent of the time in the time-accurate portion of the problem. Because computer resources had to be shared with other users, only part-time usage of 16 processors was available and the wall clock time to complete each trajectory simulation (steady state and dynamic portion) was two weeks. With dedicated usage of 64 processors on an Origin 2000, the computations could be completed in less than 2 days.

Comparisons between computed orientation and flight telemetry data showed excellent agreement in pitch and roll while the computed yaw showed a slightly larger nose outboard angle. The computed store displacements and miss distance for the supersonic case showed somewhat better agreement than for the subsonic case.

2.2.3.5 Summary of ACFD Challenge II

The quality of the invited papers and presentations reinforced the approach used by the AFCD Challenge sponsors. However, taking these presentations as representative of state of the art for applying current CFD-based tools for stores carriage and separation prediction indicates that wind tunnels will still be

relied on for the provision of the major part of the aerodynamic data on which stores certification will be safely based. Indeed, it is acknowledged that the CFD solutions were, in the majority of cases, within the error range of the wind tunnel and flight test data. Accuracy would not therefore seem to be issue, but rather the time required to produce a solution needs to be decreased significantly. Given this development, CFD-based tools should become far more prevalent in use during Requirements Definition and Systems Engineering trade-off studies for the aircraft and stores, thereby reducing the likelihood of expensive aircraft and/or store redesign after hardware has been made.

One other general result was the consensus that improvements in the ejector modeling and ejector foot/store interaction during the ejection needed to be accomplished.

One of the principal drawback of CFD Challenge II was that all the CFD results, using both Euler and Navier-Stokes, as well as a simulation that ignored the JDAM canards gave similar results. Does that mean that Navier-Stokes formulation does not have to be used, or were the test cases selected fortuitous for the inviscid formulation. Indeed, Welterlen showed that his inviscid calculation was superior to the viscous one. Since diagnostic data were not available, it is impossible to say whether the SPLITFLOW viscous formulation was at fault, or that the inviscid results had a fortuitous canceling error. It was the consensus of the participants that another CFD Challenge, one that would have diagnostic data (store and wing pressures) was merited.

Comparisons of all the results presented at ACFD Challenge II are readily available[39].

2.2.3.6 TTCP Panel WPN-TP 2 KTA 2-18

Although further CFD challenges were desirable, ACFD funding was terminated shortly after the end of ACFD Challenge II.

The Royal Australian Air Force (RAAF), Canadian Forces (CF), and the US Navy use, and will continue to use for some time, variants of the F/A-18A/B/C/D Hornet aircraft as their primary fighter weapons delivery platform. For stores clearance purposes, all these countries use similar approaches to assessing Aircraft/Stores Compatibility (ASC) based on the methodology of MIL-HDBK-1763 which has traditionally

relied heavily on the use of prior analogous stores results, wind tunnel and flight testing. Based on the demonstrated capability of CFD to predict aircraft store aerodynamics and trajectories in realistic timeframes, it appeared that CFD had the possibility to dramatically reduce wind tunnel and flight test costs and time. In order to reduce duplication and redundancy in the US Navy's Flight Clearance, Australia's ASC Clearances and Canada's Stores Clearance processes, a new Key Technical Area (KTA) was proposed under the auspices of The Technical Cooperation Program (TTCP) subgroup W. Although this KTA has only been recently approved by WPN Group, significant quantities of experimental data have already been gathered, reviewed and organized in preparation for experimental data-to-CFD prediction comparisons. The large wind tunnel Pressure Sensitive Paint (PSP) data set and store captive loads data sets from NRC/IAR's high speed tunnel have been reviewed and the appropriate data is being prepared for use in comparative studies. To date, specific subsets of the PSP data for the CF-18/MK-83 test case have been provided to interested participants under the auspices of TTCP/KTA 2-18. It should be noted that the empirical data related specifically to the test case under analysis has intentionally not been released to participating countries to date. This comparative data will not be furnished until CFD computations have been completed, in an effort to demonstrate/evaluate the true capability of CFD in solving real world stores separation problems.

CF-18/MK-83 stores separation flight-testing is ongoing at the Aerospace Engineering Test Establishment (AETE) in Cold Lake, Alberta, Canada. Flight test trajectory data have been gathered for the first test case to be analyzed under this KTA. It is anticipated that the complete flight test database for single MK-83 releases from the CF-18 will be available to KTA participants shortly.

CFD predictions by KTA 2-18 participants have not been produced to date. However, all participants have agreed upon the test case configuration. Figure 14 provides an overview of the first test case configuration being investigated by the participants.

2.2.3.7 Current US Navy Efforts for KTA 2-18

Since CFD can not be used in an everyday store clearance environment unless a junior engineer, with minimal prior CFD experience, can model a complex aircraft/store configuration and get a reasonable solution

in a timeframe of one month. In an attempt to determine the relative maturity of CFD for store separation, the US Navy decided to adopt a two-pronged approach to the problem. The approach would utilize an expert CFD practitioner using the Navier Stokes equations, and two Naval Academy Midshipmen using Euler codes.

2.2.3.7.1 The Codes Used

2.2.3.7.1.1 USM3D

The NASA Tetrahedral Unstructured Software System (TETRUSS) was developed during the 1990's to help provide a rapid aerodynamic analysis and design capability to aerodynamicists. The system is composed of several different integrated software pieces.

The USM3D[18] code is designed for the easy addition/modification of boundary conditions (B.C.). It supports the standard B.C.'s of flow tangency or no-slip on solid surfaces, characteristic inflow/outflow for subsonic boundaries, and freestream inflow and extrapolation outflow for supersonic flow. Some additional special boundary conditions are available as well.

The version of the program that was used included parallel processing. The tetrahedral grid is divided into a certain number of pieces and communication between these partitions is accomplished through Message Passing Interface. This speeds up the solution process better then the number of processors that you use. The solution is also un-affected by the splitting process.

2.2.3.7.1.2 SPLITFLOW

The other Euler code used was the proprietary code developed by Lockheed Martin Aeronautics Company SPLITFLOW[36]. SPLITFLOW is a Cartesian-based, unstructured, adaptive Euler/Navier-Stokes solver. The Cartesian approach generates hexahedral cells that are aligned with the Cartesian coordinate axes. Grid refinement involves recursively sub-dividing each cell into two, four or eight cells, which become "children" to the initial cell. Triangular faces, or facets define boundary geometry. At boundaries, cells are "cut" to account for volume and flux changes. This feature allows SPLITFLOW to handle extremely complex

geometries, and little care need be taken by the user to prepare or maintain the grid. Initial grid cell sizes are scaled from geometry facet sizes and are then refined or derefined, at specified iteration intervals, by the solver based on the user's choice of gradient adaptation functions (Mach number, pressure, etc.). The refinement applies statistical methods, and searches for high gradients to determine where cells need to be added. Since the code is "smart" enough to place cells where they are needed, the best initial grid is usually sparse and the flowfield is used to determine where new cells should be placed. With a sparse initial grid, flowfield information can propagate in fewer iterations, each of which take less time because there are fewer cells. For example, a grid limited to 800,000 cells, is appropriately initialized to about 100,000 cells. Another benefit of cutting boundary cells is that geometry changes can be made easily while salvaging a developed solution. For example, if the user has a converged solution of an aircraft with undeflected control surfaces, a new geometry model with deflected control surfaces can simply be substituted.

2.2.3.7.1.3 OVERFLOW

The OVERFLOW code is a finite difference, Chimera flow solver capable of solving the Averaged Navier-Stokes equations in overlapping grids, and is very similar to the codes used by Noak[37] and Sickles[38]. Since the developer of the PEGASUS[35] interface system ran the OVERFLOW flow solution in viscous mode for the wing, pylon and fuel tank, these predictions represent the best that can be expected from CFD.

2.2.3.7.2 Convergence History

2.2.3.7.2.1 USM3D

The density residuals for all of the test cases were usually reduced by a factor of between 2 – 3. The number of iterations also usually varied between 1200 and 2000. For the F-18/EFT, the final run was made at 1200 iterations because there was not a noticeable reduction in the residual after that and the total test took 12.582 hours on an SGI Origin 2000 running on 4 processors. The final run for the F-18/EFT/Mk-83 was made at 1500 iterations for the same reason as before and the total test took 24.825 hours on the same machine.

2.2.3.7.2.2 SPLITFLOW

The density residuals for all of the test cases were usually reduced by a factor of between 2 – 3. The number of iterations usually varied between 1000 and 2000 for this level of convergence. Since the SPLITFLOW code automatically re-grids the solution in the regions of the largest flow gradients, it was decided that an evaluation of this capability would be useful. As may be seen in Figure 15, SPLITFLOW achieves a reasonable solution at only 70,000 cells. This took only .89 hours on an SGI Origin 2000.

The solution for 235,000 and 435,00 cells was essentially unchanged. For the F-18/EFT, the final run was made at 535,000 cells because there was not a noticeable reduction in the residual after that and the total time took 48.98 hours.

2.2.3.7.2.3 OVERFLOW

The OVERFLOW code was run in the viscous mode. The viscous terms were solved on: Wing, Pylons, Fuel Tank and MK-83's using the Spalart-Allmaras Turbulence Model. The solution times were:

F-18C with Fuel Tank: $\sim 6.0 \times 10^6$ points
F-18C with Fuel Tank and MK-83's: $\sim 8.9 \times 10^6$ points

2.2.3.7.3 Test Case

During the study, there were several tests run when the F-18 had either an external fuel tank (F-18/EFT) or the combination of the external fuel tank and two MK-83 bombs (F-18/EFT/MK-83). All of the tests were run with the same test case parameters.

The test case selected was M = 0.95 and an angle of attack of 4.5 degrees. For the F-18/EFT configuration (330-gallon tank inboard, clean outboard pylon) the comparisons are shown in Figure 15. All three codes overpredict the location and strength of the shock. The most interesting result was that SPLITFLOW, with only 70,000 cells, gave a reasonable estimate of the pressure distribution.

Considering the fact that the SPLITFLOW and OVERFLOW results were achieved by college seniors, in about a months time, it appears that CFD has finally matured to the point were it can be routinely used in a production aircraft/store clearance process.

3.0 CONCLUSIONS

Will CFD replace the wind tunnel in the store separation process? In some applications, it already has. At subsonic speeds, panel methods have been routinely used to predict store loads and trajectories. The U.S. Navy has in the past used this approach to clear stores from the DC-130, P-3 and S-3 aircraft. However, at transonic speeds, where Full Potential, Euler, or Navier-Stokes codes must be used, the wind tunnel is still the preferred choice. A typical wind tunnel test will provide thousands of test data points in a typical entry (one to two weeks); even an Euler calculation would require over a year to provide the same amount of information.

Furthermore, it is not yet clear when Euler or Navier-Stokes solutions are required. If Euler is determined to be sufficient, then with the constant improvements in computer speed, it might be feasible to acquire sufficient data using a computer. In that case, it's conceivable that within several years, the wind tunnel will be supplemented by CFD calculations.

What is needed is a better understanding of how accurate CFD is in actually predicting store trajectories. For this reason, the U.S. Navy is continuously evaluating the use of computational approaches[40,41,42] and CFD challenges are planned.

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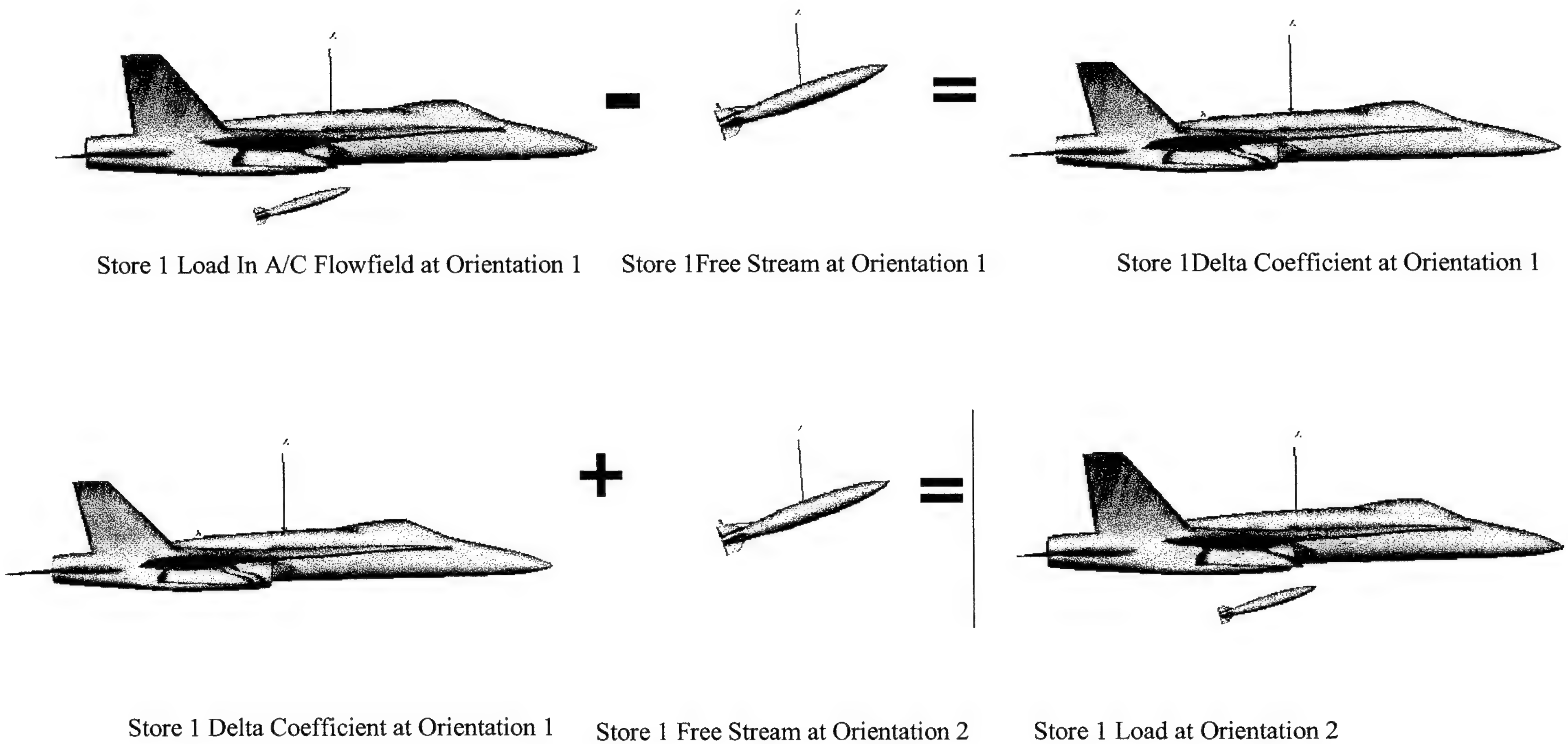

FIGURE 1 Aircraft Flowfield Effect on Store Grid loads

M = 0.90 ALPHA = 0.0 BL = 88 WL = 69

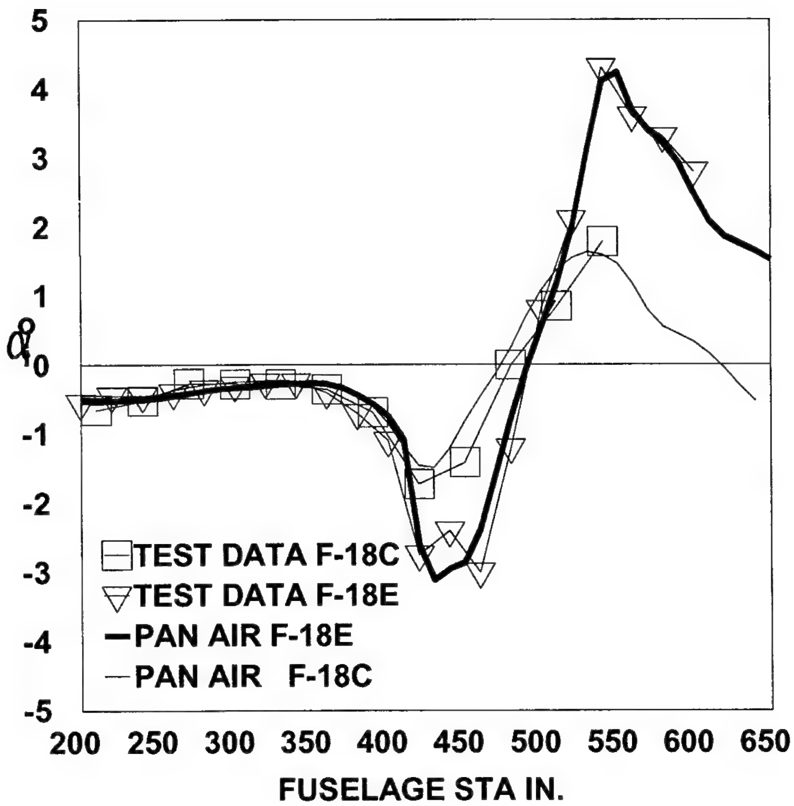

FIG 2 F-18 PAN AIR UPWASH PREDICTION

M= 0.9 ALPHA =0.0 BL 88 WL 69

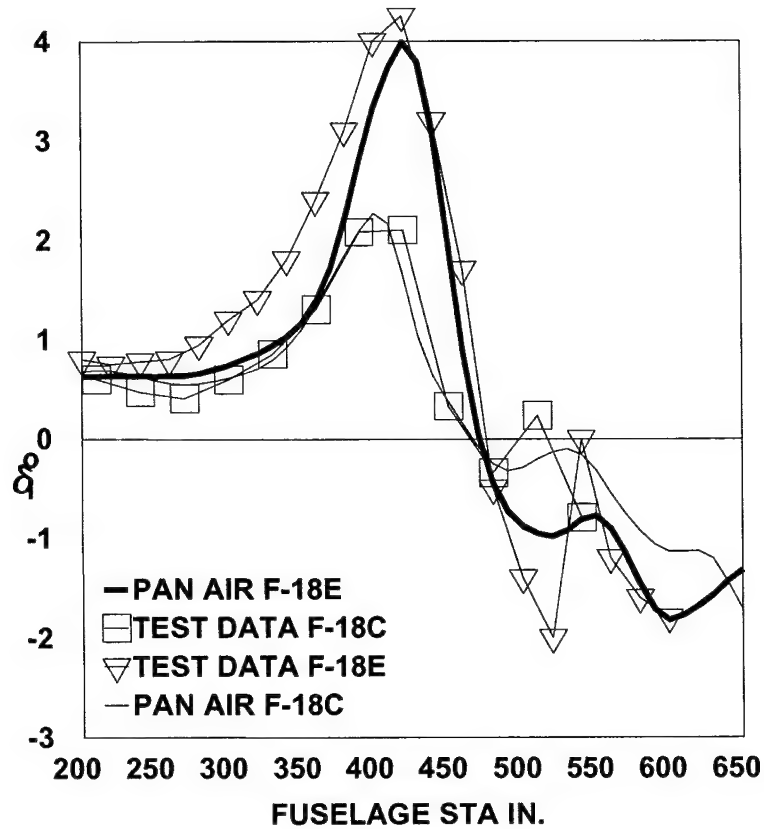

FIG 3 F-18 PAN AIR SIDEWASH PREDICTION

MID PYLON/TANK INBOARD
IFM PREDICTED F-18E INCREMENTS

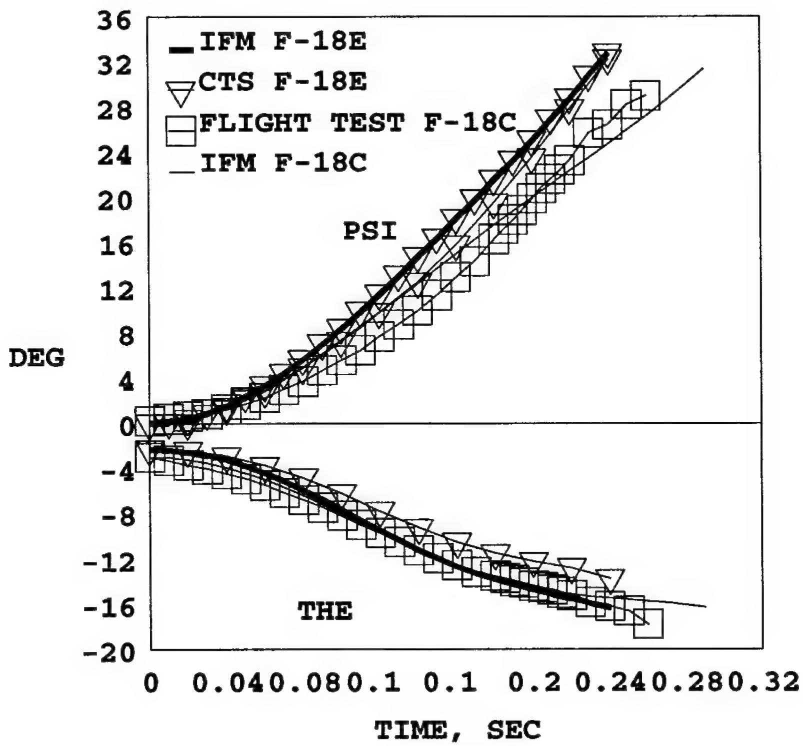

FIGURE 4 JSOW COMPARISON

INBOARD PYLON/NO TANK
IFM PREDICTED F-18E INCREMENTS

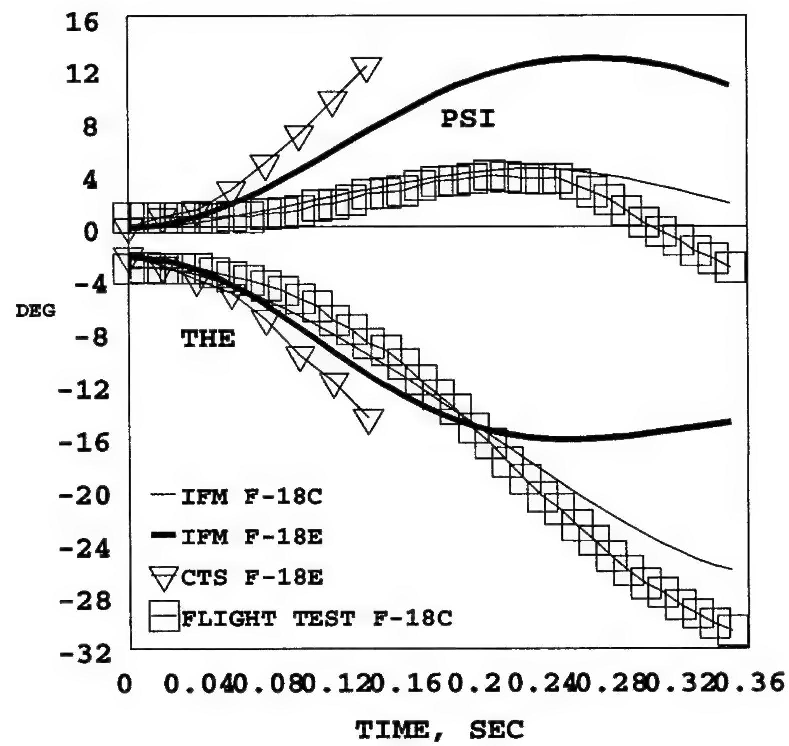

FIG 5 JSOW JETTISON PREDICTION

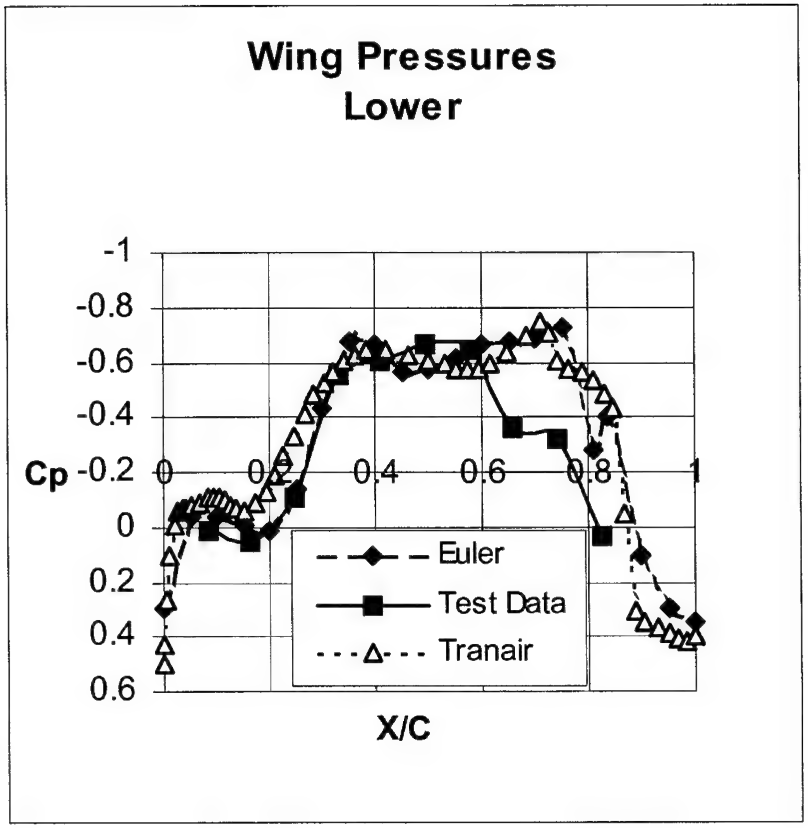

Figure 6 Wing Upper Surface C_P at M = 0.95

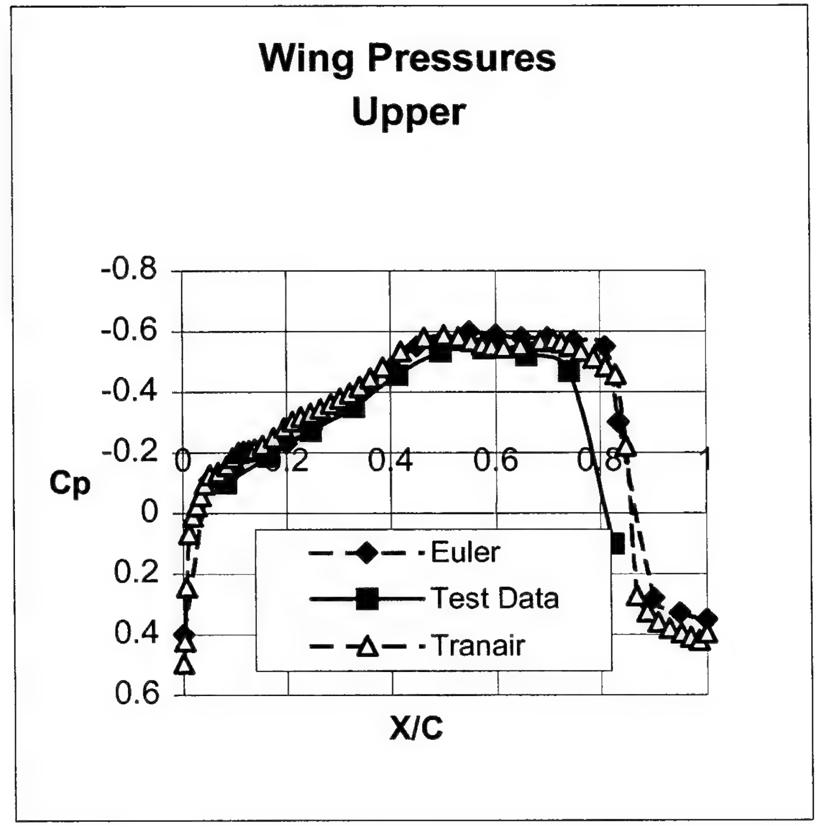

Figure 7 Wing Lower Surface C_P at M = 0.95

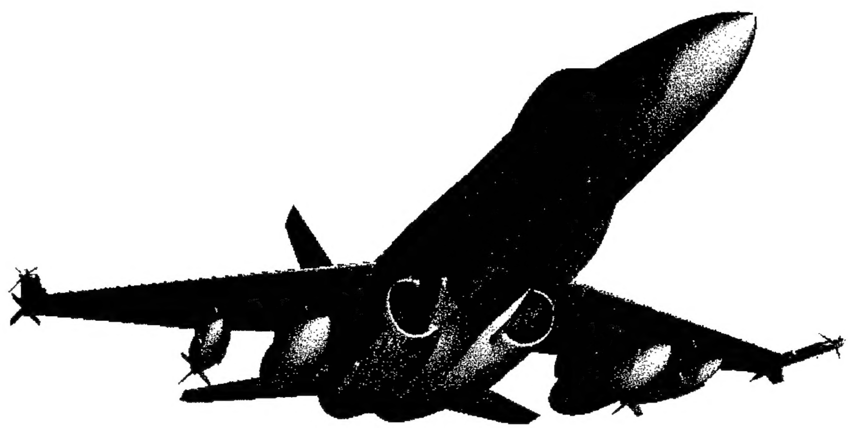

FIGURE 8 F-18/C MK-84 JDAM Configuration

FIGURE 9 MK-84 JDAM Geometry

JDAM FLIGHT 13
M = 0.962 6382 FT 43 DIVE

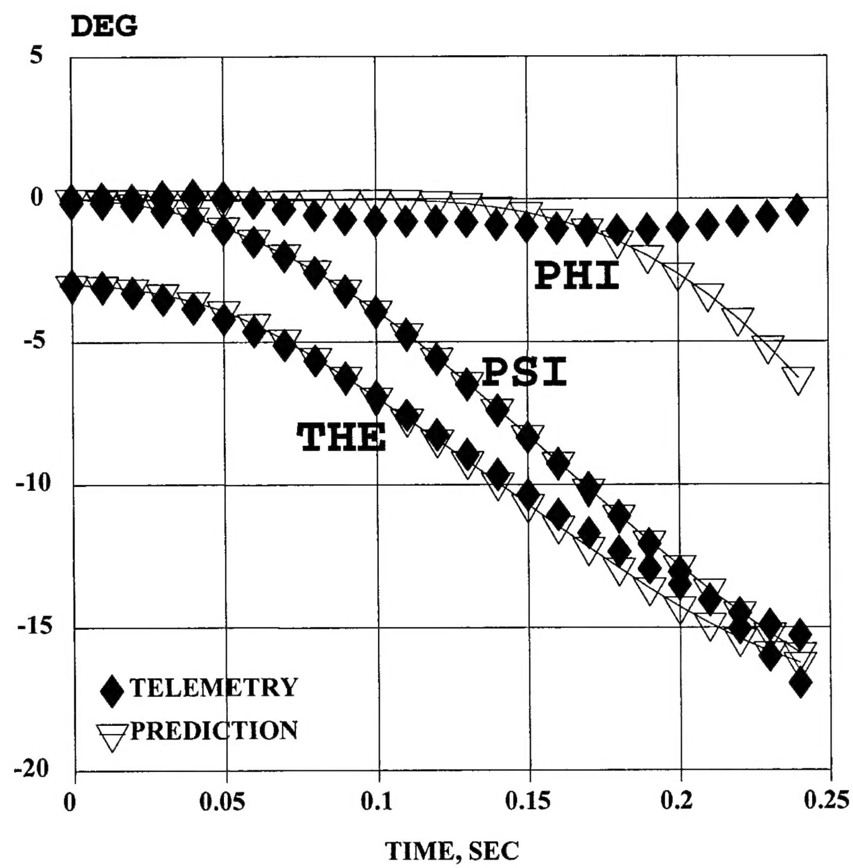

FIGURE 10 JDAM ATTITUDES

JDAM FLIGHT 14
M = 1.055 10832 FT 44 DIVE

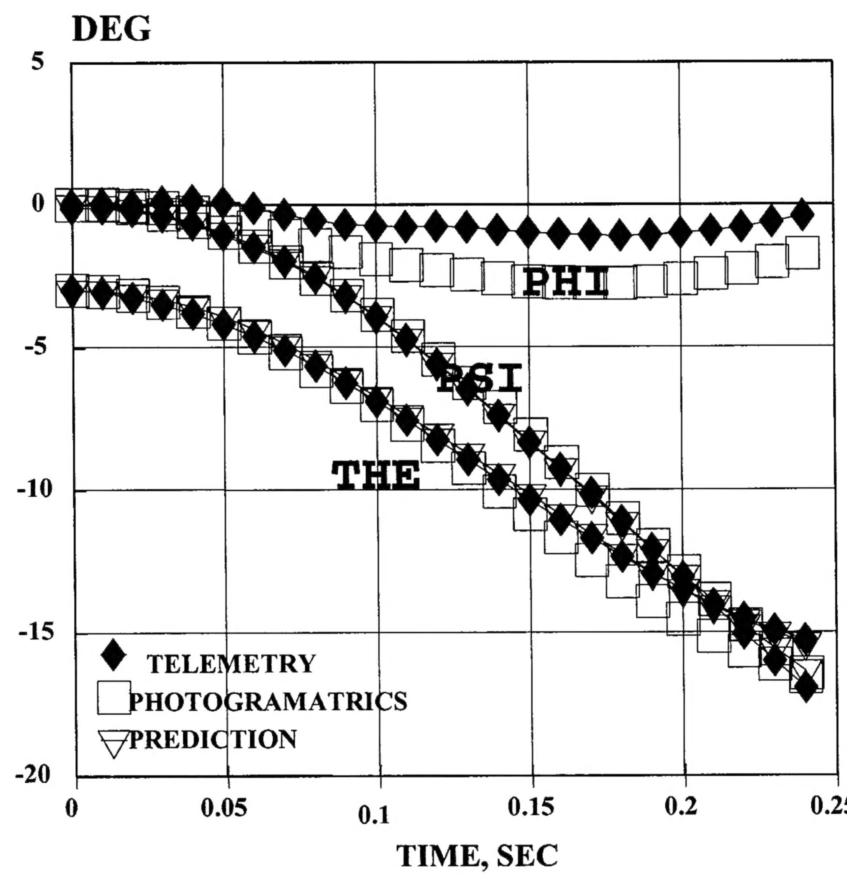

FIGURE 11 JDAM ATTITUDES

JDAM FLIGHT 13
M = 0.962 6382 FT 43 DIVE

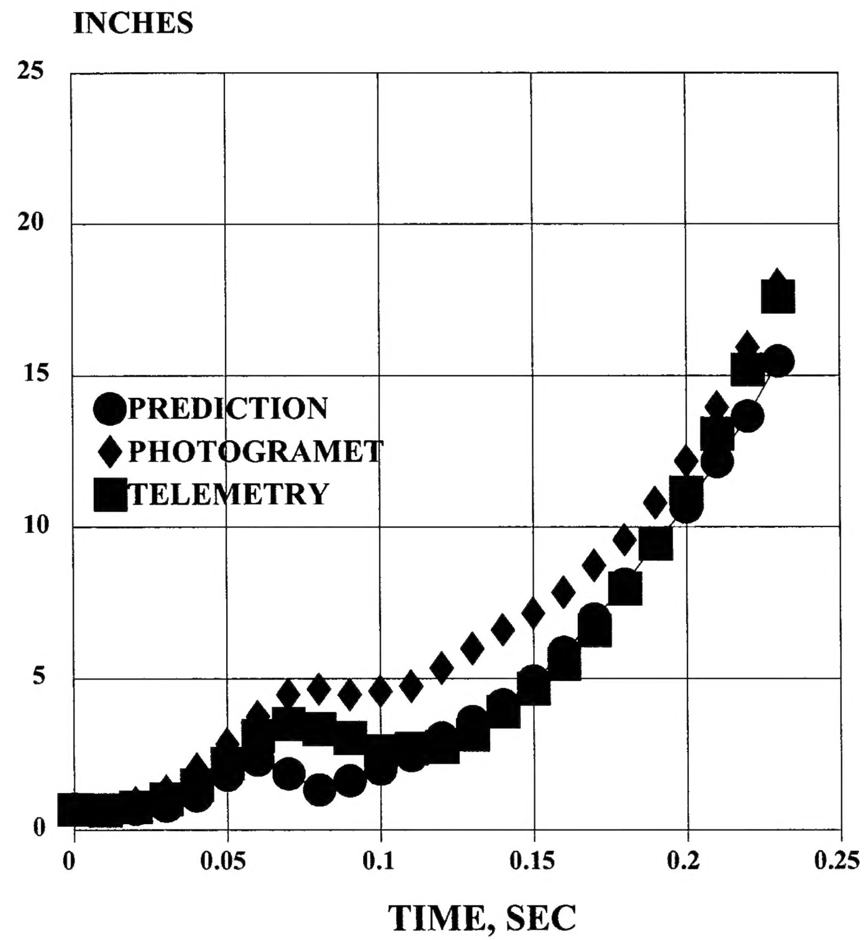

FIGURE 12 JDAM MISS DISTANCE

JDAM FLIGHT 14
M = 1.055 10832 FT 44 DIVE

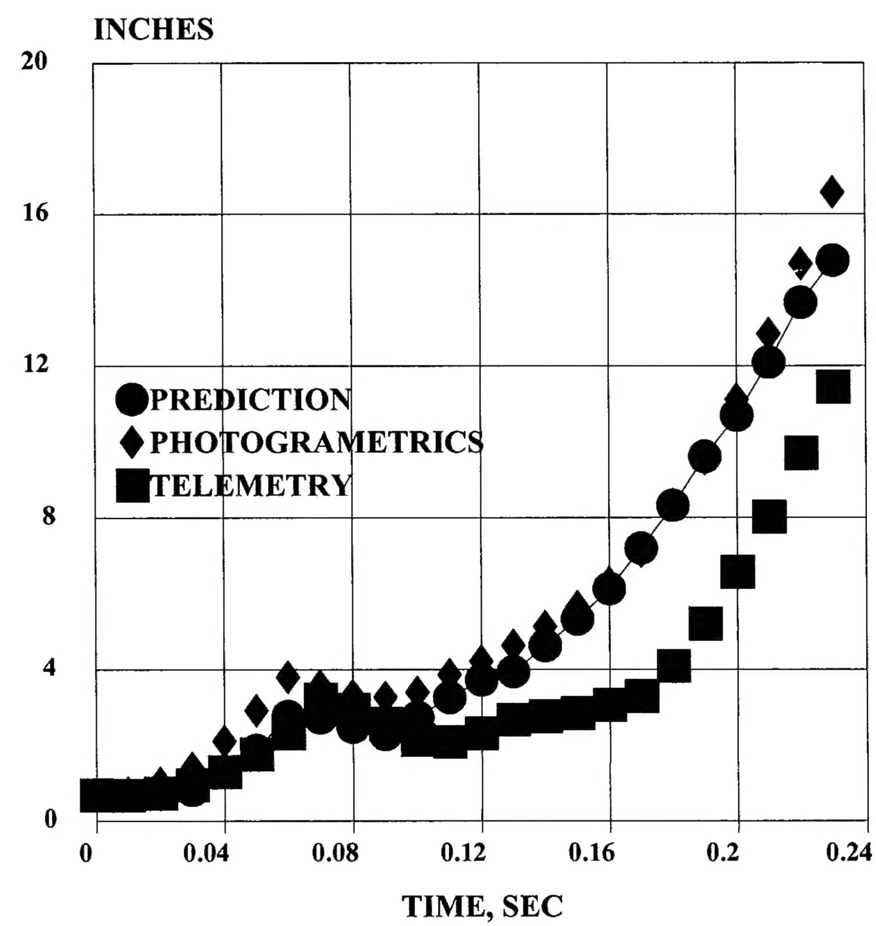

FIGURE 13 JDAM MISS DISTANCE

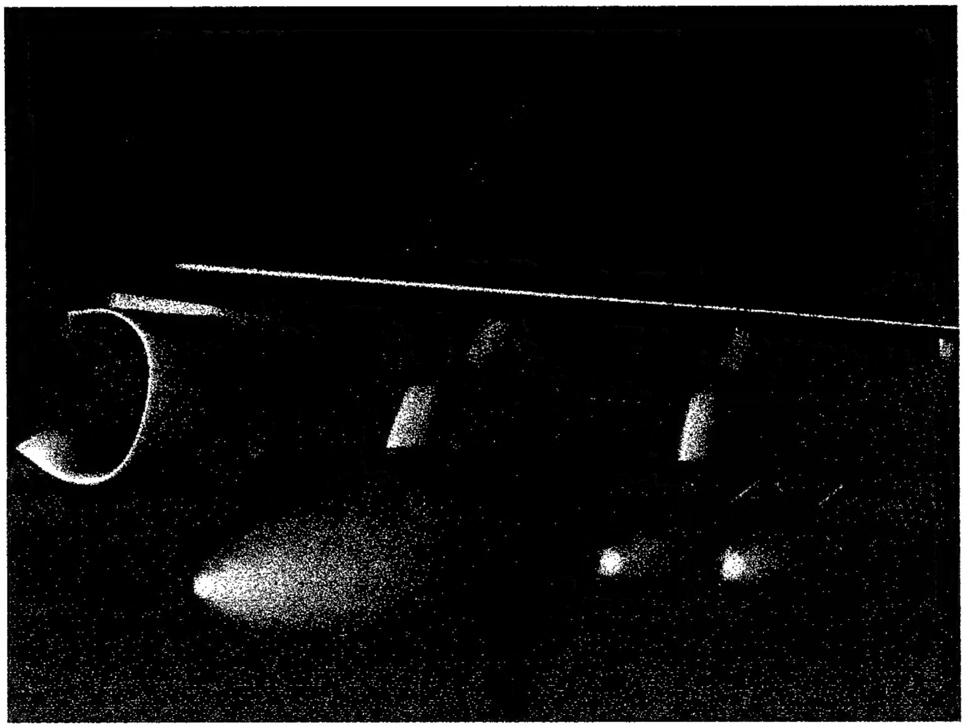

FIGURE 14 CF-18/MK-83 Configuration

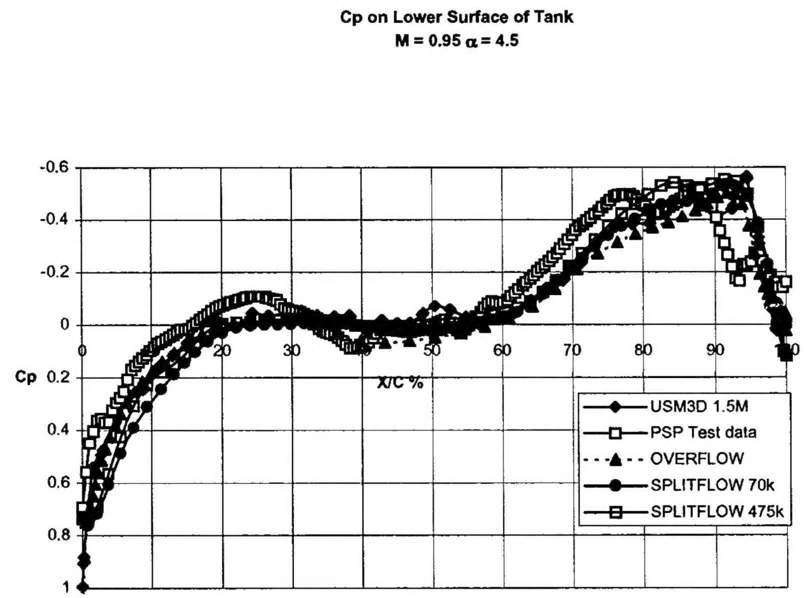

FIGURE 15 Euler/OVERFLOW Comparisons on Fuel Bottom